Six-Terminal Connection— Another Step in Improved Measurement Accuracy

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Six-Terminal Connection – Another Step in Improved Measurement Accuracy

Accuracy in impedance measurement is in many cases directly dependent on how test leads are connected to the component under test. Four-terminal measurement connection can solve the problem of lead resistance appearing in measurement results. However stray shunt (parallel) impedances can be another source of error, especially in AC impedance measurements.

Dealing with the shunt impedances requires looking at some additional measurement connections. Ultimately, we'll be looking at a six-terminal connection as a solution.

Four-Terminal Connection*

Figure 1 helps illustrate the reasons for four-terminal connection in impedance measurements.

Remember that capacitance, resistance, or inductance are not measured directly. Impedance isn't even measured directly. The process is to apply a drive signal to the unknown, Zu, then the effect of Zu on the drive signal is measured.

In Figure 1, the drive is a known current, I, and the measured quantity is voltage, V. From these two parameters, the unknown impedance, Zu, can be computed as Zu=V/I. For AC measurements, additional parameters of drive frequency and phase relationship of V and I allow further calculation of R, L, or C values associated with Zu.

Following this process for the two-terminal connection in Figure 1a, drive current is forced through the meter leads and Zu. The resulting voltage, V, is also measured with the same two leads. Thus, V contains not only the voltage drop caused by Zu, but the voltage drops caused by lead and contact resistances, R1 and Rc. This creates significant measurement error for low values of Zu (small R, small L, or large C).

The problem is solved, however, by the four-terminal connection in Figure 1b. Here, the metering circuit is connected by a separate set of leads. Because of the meter circuit's high impedance, no current flows through it; the meter sees no voltage drop across its leads or contacts. As a result, the measured voltage is just that appearing directly across Zu. To state this in terms of current, the current in a loop is the same everywhere in the loop and since we have a known current, the effect of the lead and contact resistance in that path makes no difference in the current through Zu.

The needed values of V and I have now been determined and are not dependent upon the lead and contact resistances.

*For a more complete treatment of 4-terminal connection see the Fall 1983 issue of BRIDGE magazine.

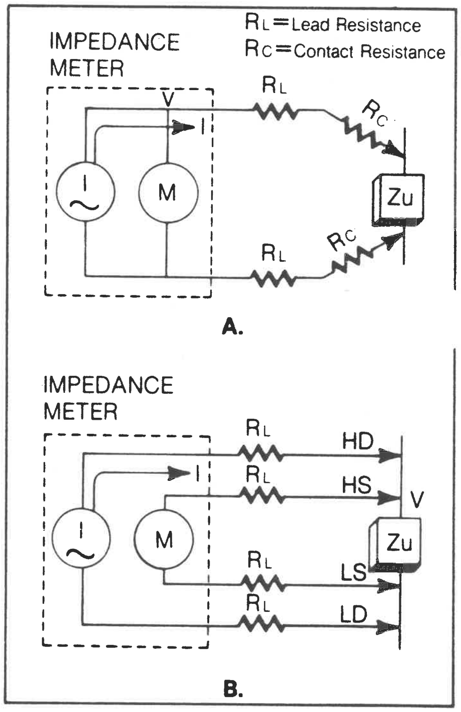

Figure 1. A: Two-terminal connection. B: Four-terminal connection. The two-terminal technique is the simplest approach, but introduces series lead and contact resistance into the measurement. A four-terminal connection places the high-impedance meter directly across the unknown, Zu, eliminating lead and contact resistance errors.

For in-circuit measurements, the shunt effects are from other circuit components and will generally be significant regardless of the value of Zu.

Other Sources of Impedance Measurement Errors

While the four-terminal method alleviates lead and contact resistance problems, it fails to attack some other possible sources of impedance measurement error.

Consider, for example, the problem of in-circuit measurements. This is illustrated in Figure 2a. There, the problem is to measure Zu without including the effects of other circuit components. The old method of isolating Zu by breaking its connections to other circuit components is no longer a solution, since many circuits are screened onto substrates.

Even for loose components, the problem of isolation still exists. This is illustrated in Figure 2b. There, a metal-encased capacitor is shown to have numerous stray components associated with it. Contaminants across the lead-to-case insulators provide resistive leakage paths, and stray capacitance exist between the capacitor leads and between the capacitor plates and the case. Even for an epoxy encased capacitor, stray capacitance will exist from each plate to any nearby conductor, such as the metal parts of a test fixture.

For either in-circuit measurements or loose component measurements, the problem generalizes to what is shown in Figure 2c. Zu is shunted by other impedances.

The shunt impedances for loose components tend to be rather large, resulting from high value leakage resistances and small stray capacitances. So, if Zu is small (small R, small L, or large C), shunt errors become negligible for low test frequencies. However, at higher frequencies or for large Zu (large R, large L, or small C), shunt effects take on more significance. For in-circuit measurements, the shunt effects are from other circuit components and will generally be significant regardless of the value of Zu.

So the problem in most high-accuracy AC measurements is to eliminate or reduce the effects of shunt impedances.

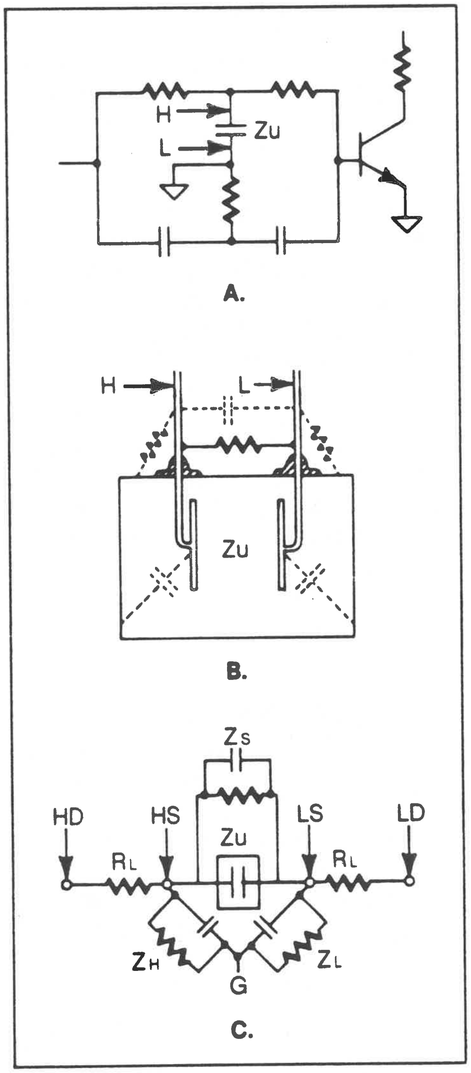

Figure 2. A: In-circuit measurement. B: Loose component. C: The equivalent measurement problem. In either in-circuit or loose component measurement, the measurement problem reduces to the same things–dealing with lead resistances, R1, and high- and low-side shunt impedances, ZH and ZL.

Fifth-Terminal Guard an Improvement

The stray shunt impedances that exist between the measurement leads and fixture connection point can be intercepted by using shielded test leads (such as coax cable) and proper shielding of the test fixture. These shields can be connected together and to other points in the circuit (such as G in Fig. 2c). This shielding does not eliminate the strays, it actually adds more because of the capacitance between the test leads and their shields. It does however control them so they can be directed to a common point (let's call this point guard).

Nothing yet has been accomplished unless this common point is properly connected so all the current paths can be accounted for. We must be certain that the only current being measured is the current flowing through the unknown. Figure 3 shows the use of a separate current meter in an attempt to evaluate just the current through Zu with all other currents flowing through the stray paths separated from this measurement current. This 5th terminal guard connection (Gd) works only if the current meter resistance and its lead resistance Rml is very low compared with ZL, causing most of the current to flow through the unknown, Zu, rather than ZL.

The current through the high side strays IH causes no problem because it flows back to the source without modifying the measurement current Iu. We still have a problem, however, because the stray current from the high side (IH) flows through guard lead resistance RH, which raises the potential of point G. This causes current to flow through ZL. The measurement current is therefore modified resulting in an error in the measured impedance Zu.

The Sixth Terminal

Further improvement can be made by connecting the current meter to a 6th terminal (Gs) allowing separate sensing of the measurement current, thereby eliminating the effects of the voltage across RH. This provides an improvement in guarding out the shunt impedances. But as ZL becomes smaller and closer to the impedance of the meter circuit (Rml, Rm, Rl), this method becomes less effective.

Active Guard

Since the high side current (IH) cause no measurement error it seems that the only source of currents causing measurement errors are those that flow through ZL. If a circuit could be devised to hold the voltage at both ends of ZL at the same value there would be no current flowing through it to cause errors. One such circuit is shown in Figure 4.

Figure 4 illustrates the modern six-terminal, active guard measurement circuit. Here, the input of a very high gain operational amplifier is connected between LS and "guard sense" thus across ZL. Since the input voltage of a very high gain amplifie near zero there is near zero current flow through ZL, and LS is at virtual ground. ZL is guarded out. RL causes no problem because there is no current drawn through it due to the high impedance of this amplifier. ZH still draws drive current, but this is not part of the measurement current. This amplifier can also be used as the unknown current measuring system. With no current through ZL, all of the current through Zu must flow through the feedback resistor (RSTD). None will flow into the high impedance amplifier input. This causes a voltage drop in RSTD exactly proportional to the unknown current which is sensed by a differential amplifier.

Figure 3.

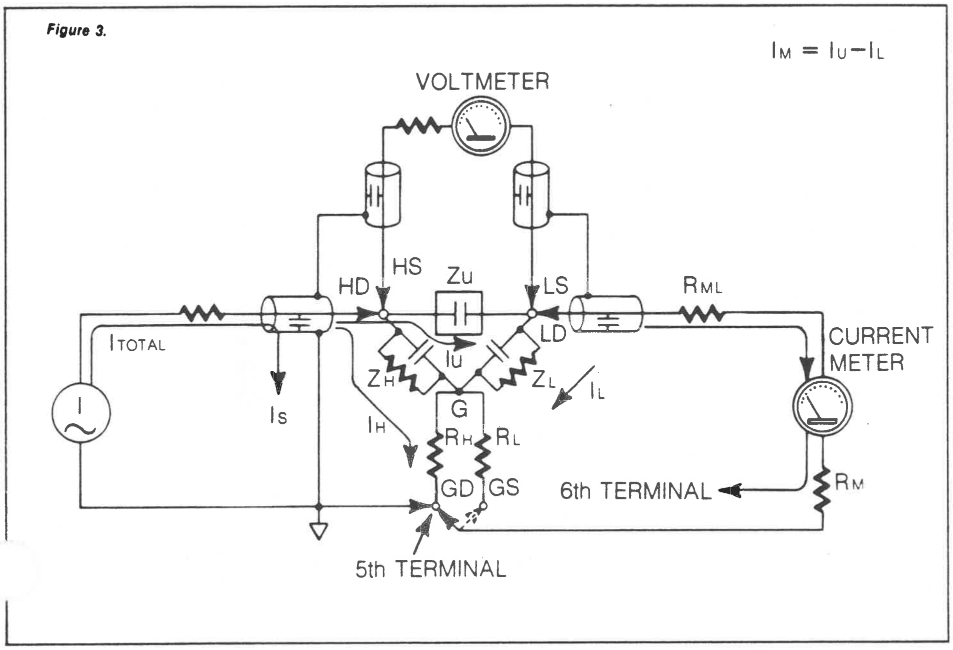

Figure 4.

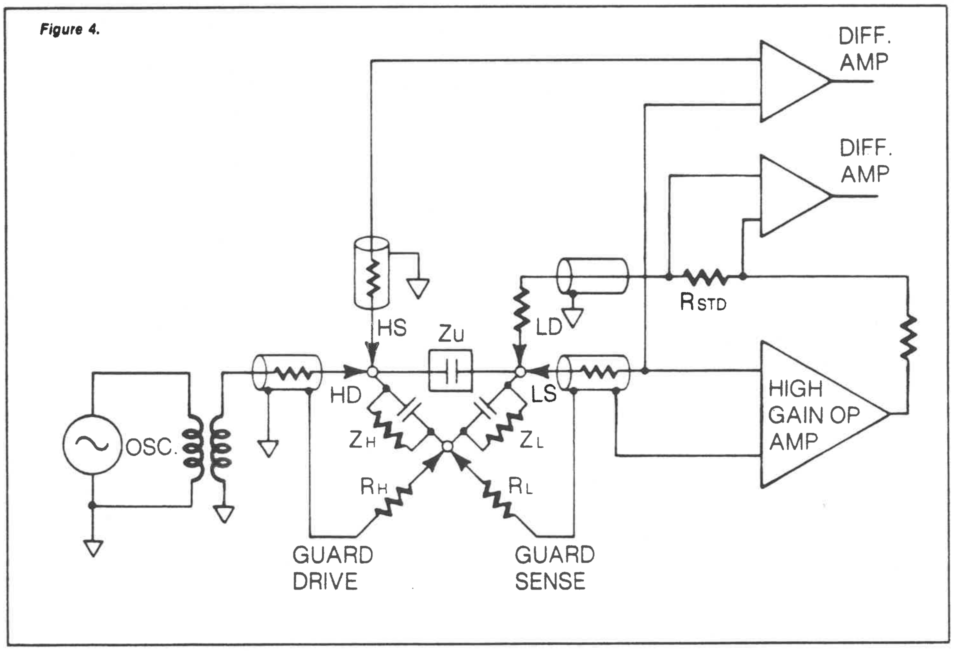

Figure 3. Shielding and guarding are different. For guarding to occur, the shunt impedances must be eliminated or absorbed by using a fifth terminal in the measurement configuration.

Figure 4. Modern six-terminal impedance measurement configuration using active guarding with separate guard drive and guard sense leads to eliminate guard-lead error.

Notice that there are separate guard drive and guard sense leads. This uses the same concept discussed in four-terminal connections where guard lead error is eliminated by the second connection for the high-impedance sense circuit. High impedance sensing is ensured throughout by using differential amplifiers.

Now Zu and the shunt impedances can have very low values and accurate measurement of Zu will be maintained through full guarding and elimination of lead and contact resistance effects from the measurement.

To find out more about which instruments offer these various terminal configurations and which is best for your application, contact your local ESI representative. Or call our toll-free number, 1-800-547-1863. ■

The author:
Armen Grossenbacher was first introduced to electronics as a Navy Electronics Technician. After leaving the service, he attended Devry Technical Institute in Chicago, where he graduated first in his class. He received his Bachelor's and Master's degrees in applied science from Portland State University. Armen joined ESI in 1951. He has managed both assembly and production, and is currently engineering manager for the Instrument Business Unit.